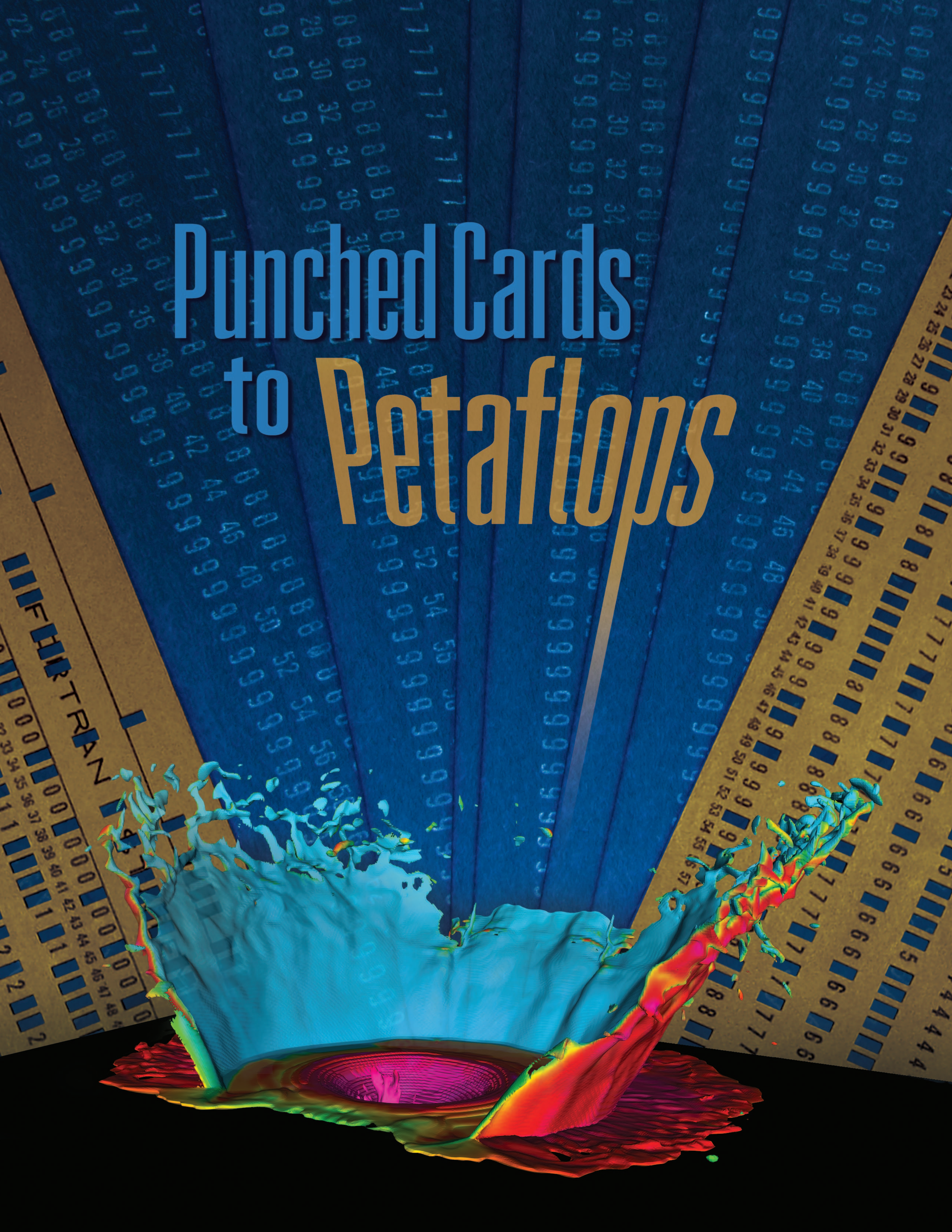
Punched Cards to Petaflops



Using the most-advanced computers of that time, by 1952 Los Alamos built and tested Ivy-Mike, the world's first full-scale hydrogen bomb. It achieved a yield equivalent to 10,400,000 tons of TNT. (Photo: Los Alamos)

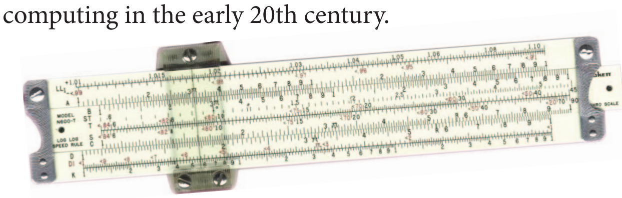
In May 2008, Los Alamos National Laboratory's Roadrunner became the most powerful supercomputer in the world. The coveted title of world's most powerful supercomputer changes hands often, but Roadrunner was not just another fast machine. Its pioneering architecture allowed Roadrunner to break the petaflop computing barrier by performing more than a thousand trillion floating-point operations (calculations) per second. In doing so, Roadrunner sparked a technological revolution.

Computing has provided the tools for the solutions of many problems in nuclear science that would otherwise have been either intractable or much delayed.

Los Alamos enjoys a rich history of innovation in many fields, including supercomputing. As Laboratory Fellow Jack Worlton wrote in 1978, "Nuclear science has provided technical motivation and much of the funding for large-scale scientific computing, and computing has provided the tools and techniques for the solutions of many problems in nuclear science that would otherwise have been either intractable or much delayed." Decades before the petaflop barrier was broken, the Laboratory relied on mechanical desktop calculators and punched-card machines to perform calculations necessary for building the first nuclear weapons. This relationship, between national security and computing, is no mere coincidence.

Early Computing and the Manhattan Project

For millennia, humans have needed calculating tools to perform an assortment of tasks, including basic arithmetic, records management, and timekeeping. In the 17th century, important devices such as the slide rule and the first mechanical calculator were invented, but it was not until the late 19th century that computers capable of interpreting data, such as advanced punched-card machines, were developed. Punched-card technology remains with us today, but it gradually fell out of favor as a platform for state-of-the-art computing in the early 20th century.



The slide rule is a simple, mechanical analog computing device that uses distance to represent real numbers.

In the decades leading up to World War II, complex analog computers rose to prominence. Analog computers use measurable physical entities, such as distance or voltage, to represent numerical data. Although analog devices, such as the astrolabes used by early navigators and astronomers, have been around for thousands of years, analog computers remained relatively simple machines until

Early punched-card technology was used for many applications, including controlling machines such as the player piano.

Mechanical calculators, such as the Marchant, were used heavily at the wartime Laboratory. (Photo: Los Alamos)

the early 20th century. The development of advanced analog computers culminated with MIT's differential analyzer, a machine named for its ability to solve complex differential equations. The differential analyzer was invented by Vannevar Bush and his student Harold Hazen.

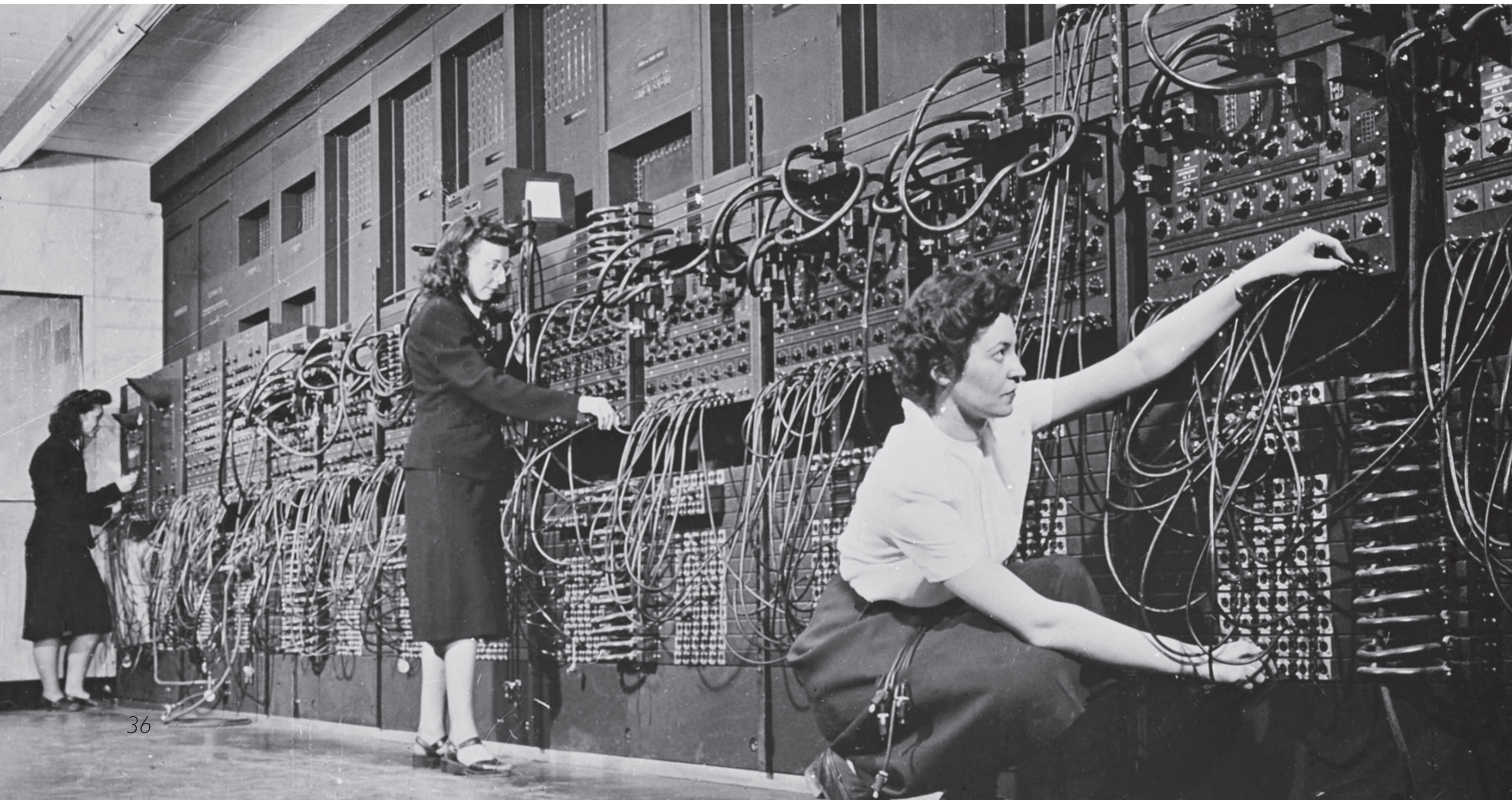
As the 1930s drew to a close, both Bush and his machine were drafted for defense projects. On the eve of the country's entry into World War II, research on critical defense technologies, such as radar, was performed at the MIT Radiation Laboratory using tools that included the differential analyzer. Bush managed several important programs as head of the National Defense Research Committee (NDRC) and later accepted a new position as head of the Office of Scientific Research and Development.

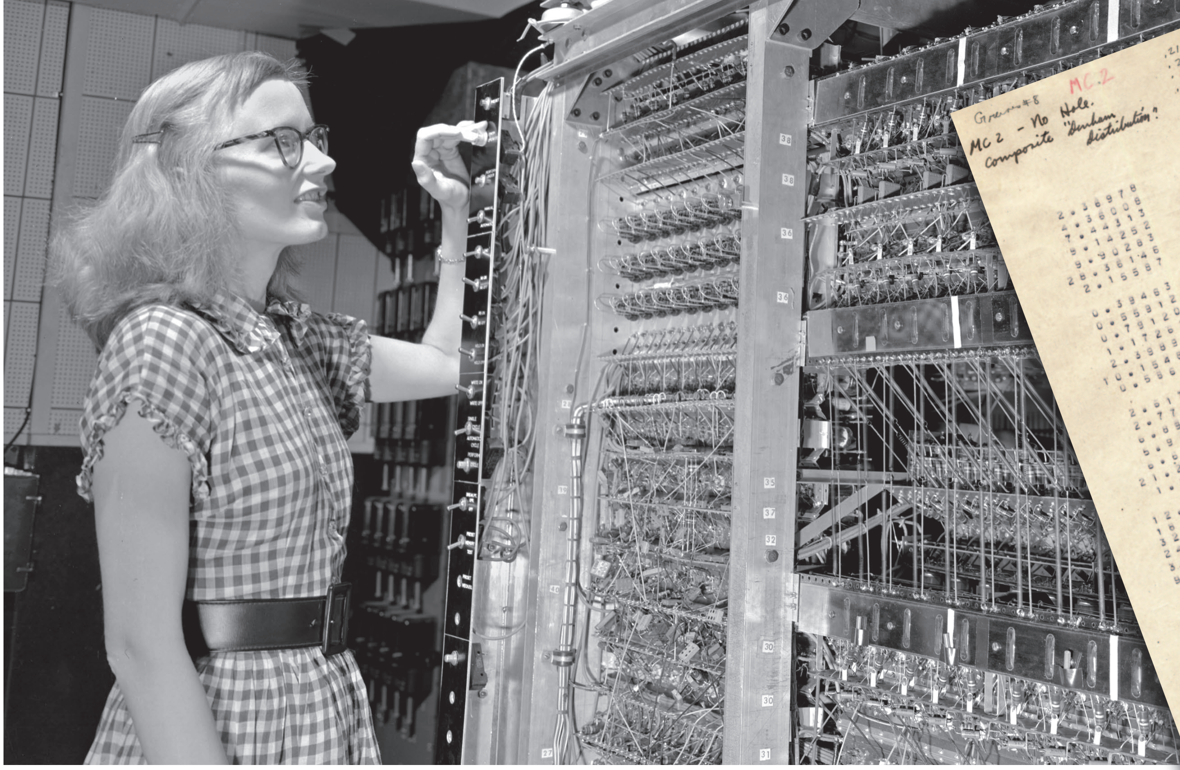
The NDRC programs included the germinal atomic bomb project, which Bush took a personal interest in. After the Japanese attack on Pearl Harbor, the bomb project grew rapidly and, with Bush's concurrence, was transferred to the Army Corps of Engineers. The project came to be called the Manhattan Project, and the weapons design laboratory, sited northwest of Santa Fe, New Mexico, was known as Project Y.

From the very beginning, Los Alamos National Laboratory relied heavily on computers and computing machines.

From the very beginning, Project Y (which eventually became Los Alamos National Laboratory) relied heavily on computers and computing machines to design the world's first atomic bombs. When the Laboratory commenced operations in the spring of 1943, several mechanical calculating machines were purchased. These devices, the most useful of which was the Marchant desktop calculator, were primarily used to perform calculations in support of the gun-assembled uranium weapon program (Little Boy). Relatively powerful IBM punched-card machines soon followed, thus enabling more-complex computing in support of the implosion-assembled plutonium weapon program (the Trinity device and Fat Man).

Digital computers, such as the ENIAC, use numerical digits to represent data. (Photo: Los Alamos)





An operator inspects the MANIAC computer. MANIAC produced coded, numerical printouts, such as this one on the right. (Photo: Los Alamos)

In a gun-assembled device such as Little Boy (foreground), a uranium projectile is propelled at a uranium target to initiate the fission chain reaction. Plutonium requires a more complex method of assembly known as implosion. In implosion devices, such as Fat Man (rear), a sphere of plutonium is compressed by high explosives to initiate the fission chain reaction. (Photo: Los Alamos)

Early on, the wartime computing machines at Los Alamos lacked mechanical reliability and, largely as a result, required routine repairs and often yielded inaccurate results. But the early computing program at Los Alamos boasted several notable scientists, Richard Feynman (who would win the 1965 Nobel Prize in Physics) and Nicholas Metropolis among them. Feynman and Metropolis decided to personally start repairing the Marchant and punched-card machines. As Metropolis and his Los Alamos colleague Eldred C. Nelson said after the war, "When the [Laboratory] administration discovered this extracurricular activity, some critical eyebrows were raised and service was interrupted. Then, as the number of working computers dwindled, criticism turned to pleas to restore the status quo."

Despite the lack of reliability, the early computing technology became nearly indispensable, especially as Feynman and Metropolis grew more adept at maintaining them, enabling the scientific staff to model complex experiments. The data produced in these models helped scientists understand the physics of implosion. Likewise, computing enabled scientists to accurately predict other physical scientific phenomena, such as the weapon's explosive yield, pertaining to the Trinity test of July 16, 1945.

A few weeks after the Trinity test, atomic bombs were used to help bring World War II to an abrupt and victorious conclusion.

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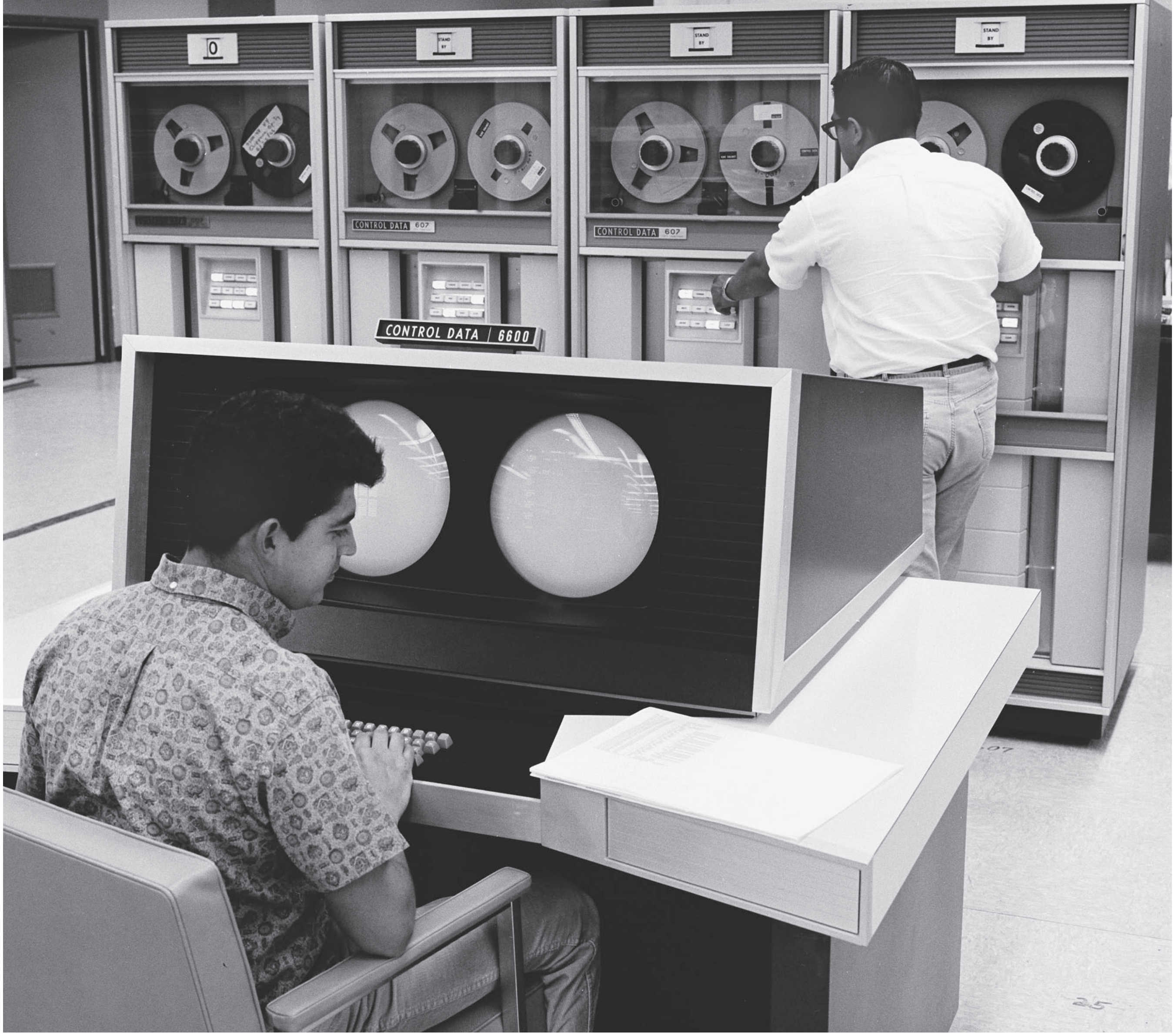
The eminent Hungarian mathematician, John von Neumann, also played an important part at Project Y as a consultant. Von Neumann introduced the Los Alamos staff to many cutting-edge computing technologies, including the world's first electronic digital computer, the ENIAC (Electronic Numerical Integrator And Computer), which was under construction at the University of Pennsylvania. ENIAC was designed to make calculations for the Army's artillery firing tables, whose data helped gunners accurately aim their weapons. ENIAC's versatile architecture also enabled it to perform calculations in support of early hydrogen



The CDC 6600, the first computer to break the megaflop barrier, is generally regarded as the world's first supercomputer. *(Photo: Los Alamos)*

bomb research. In fact, ENIAC's first job was a hydrogen bomb calculation for the Los Alamos staff. ENIAC, then still unknown to the public because its existence was classified, had quietly ushered in the age of modern computing.

Marchant desktop calculators and IBM punched-card machines continued to see service at the Laboratory for years after the war. But the quest for more-complex and more-powerful weapons called for more-complex, and more-powerful computers. As Metropolis and Los Alamos physicist Frank Harlow remembered, the "experience of the war years was enough to excite the involved scientists and engineers to the power of mechanized calculations and acted as a tremendous spur to the postwar development of the modern computer."

Cold War Computing

In the months and years following World War II, scientists at Los Alamos refined fission weapons and explored the feasibility of building the hydrogen bomb, a weapon many orders of magnitude more powerful than Little Boy and Fat Man. Von Neumann arranged for the ENIAC to run some of the early hydrogen bomb calculations in Pennsylvania, but it soon became clear that Los Alamos needed its own modern computer. Metropolis, who was working at the University of Chicago, accepted an invitation to return to Los Alamos to build such a machine.

The ENIAC had spawned the development of several similar computers. Metropolis, who consulted with von Neumann, studied several of these computers and designed the Los Alamos version to be more powerful and user friendly. He called it the Mathematical Analyzer, Numerical Integrator, And Computer, or MANIAC for short. As construction started in 1948, research on the hydrogen bomb progressed steadily. In the months after the Soviets conducted their first atomic bomb test, in August 1949, work on the hydrogen bomb accelerated.

In early 1952, the MANIAC was completed. Several months later, on October 31, the hydrogen bomb—the world's first full-scale thermonuclear device—was tested at Enewetak Atoll in the Pacific. The test, dubbed Ivy-Mike, unleashed a blast equivalent to nearly 500 Fat Man–type bombs and completely vaporized the small island it was conducted on.

The innovative Connection Machine, CM-5, was the first massively parallel supercomputer at Los Alamos. It was built by the Thinking Machines Corporation. *(Photo: Los Alamos)*

Computers played no small role in the timely success of Ivy-Mike. As the Laboratory's second director, Norris Bradbury, stated in 1954, "Computers are an essential part of any thermonuclear computation. They have a very great task to play because the computations in this field are not things you make with a slide rule or a small pad of paper." He concluded, "Only recently, with the development of machines such as the MANIAC, the computer at Princeton, [and] IBM computers, have we had the machines which even begin to attack the problem which was confronting us."

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The MANIAC line of computers enjoyed a long and successful run at the Laboratory and beyond. The MANIAC II, which was completed in 1956, was easier to operate than the original. After more than 20 years of service, MANIAC II was shut down in 1977. Metropolis also constructed a third machine, MANIAC III, at the University of Chicago in the early 1960s. But in the 1950s, as digital electronic computing technology became less expensive, more reliable, and more powerful, commercially produced computers started to gradually displace ENIAC's handmade descendants.

The Laboratory purchased its first commercial computer, an IBM 701, in 1953. The acquisition of the 701 opened a new era in Los Alamos computing, which would be dominated by commercial machines and custom computers developed jointly with corporate partners. Throughout much of the 1950s and 1960s, the Laboratory managed to double computing capacity every two years. This remarkable achievement was made possible through partnerships with private companies and breakthroughs in computing technology.

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The most significant advancement during this era was the development of transistors. Up to that point, computers relied on vacuum tubes, which produce heat and require routine replacement, to control electric currents. The ENIAC, for instance, contained over 17,000 vacuum tubes. Transistors, on the other hand, were smaller, more reliable, cheaper, and less complex. To meet the growing computing needs of the weapons program, in 1961 the Laboratory received an IBM Stretch, the company's first transistor computer**.** Although the Stretch never achieved the lofty performance goals set by IBM, it retained the title of world's fastest computer into the mid-1960s.

Los Alamos scientists next looked to Control Data Corporation (CDC) for machines with even more power. CDC delivered by producing the world's first supercomputer, the model 6600. The 6600s, which were the first computers capable of performing a million floating-point operations per second (megaflops), were soon supplemented by even faster CDC 7600 models.

Seymour Cray, the CDC designer who led the development teams that produced the 6600 and 7600, left the company to start his own in 1972. His company, Cray Research, completed its first design, the revolutionary 160-megaflop Cray-1, in 1975 and delivered it to Los Alamos the following year. The Cray-1 used integrated circuits (individual chips containing numerous transistors) to improve performance and an innovative Freon cooling system to ensure the machines did not overheat. Seymour Cray also used revolutionary "vector" processing, which enabled the Cray-1 to process infor-mation far more efficiently than any other computer of its day. During the 1980s, the Laboratory purchased additional Cray computers, most notably the X-MP. From 1982 to 1985, the X-MP, which used multiple "vector" processors, reigned as the world's fastest computer.

Seymour Cray with the Cray-1. The Cray-1's elegant shape increased performance by decreasing the length of signal-carrying wires. *(Photo: Cray Inc.)*

The women who operated the wartime Laboratory's desktop calculators and punched-card machines were themselves were called "computers." They often were the wives of Los Alamos scientists. *(Photo: Los Alamos)*

Supercomputers would change almost as rapidly and as drastically as the global political landscape of the early 1990s.

As the 1980s drew to a close, Los Alamos remained a key driver in the evolution of computing by once again partnering with IBM and starting a collaboration with the Thinking Machines Corporation. Thinking Machines' massively parallel Connection Machine series, which used thousands of microprocessors to perform numerous calculations simultaneously, would take Los Alamos into the gigaflop era (a billion floating-point operations per second), which had already been opened by the Cray-2 elsewhere. But the fortunes of Thinking Machines, despite its innovative lineup of supercomputers, would change almost as rapidly and as drastically as the global political landscape of the early 1990s.

Computing Since 1992

As the Cold War came to an abrupt end, government funding for supercomputers shrank. These cutbacks played a role in bankrupting Thinking Machines in 1994 and Cray Computer Corporation, an offshoot of Cray Research, the following year. But just as these companies went out of business, Congress created the Science-Based Stockpile Stewardship Program "to ensure the preservation of the core intellectual and technical competencies of the United States in nuclear weapons, including weapons design, system integration, manufacturing, security, use control, reliability assessment, and certification." Specifically, the new law called for "an increased level of effort for advanced computational capabilities to enhance the simulation and modeling capabilities of the United States with respect to the detonation of nuclear weapons." As such, the Accelerated Strategic Computing Initiative (ASCI) was launched to rapidly develop the much more powerful computers necessary to sustain the Stockpile Stewardship Program.

The success of ASCI came largely as a result of unprecedented levels of cooperation between the national laboratories and private industry. At Los Alamos, the partnership with Cray resumed with a trio of machines in the mid-1990s.

The evolution of the computer between the 1940s and 1960s, as told by Patsy, Gail, Milly, and Norma. *(Photo: U.S. Army)*

The T3D, which arrived first, marked Cray's entry into massively parallel computing, and the T90 and J90 machines, which came soon after, pushed vector technology to its limit. But for ASCI to meet its national security goals, computing would need to make the technological leap from billions to trillions of floating-point operations per second (teraflops). A new architecture, parallel clusters, would make it possible.

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As its name implies, a parallel-cluster computer is actually many computers that function together as a single unit. The Laboratory's first parallel cluster machine, Blue Mountain, was a collection of 48 Silicon Graphics computers. The system could perform 3 trillion floating-point operations per second, making it the world's third-fastest computer in 1999. Blue Mountain trailed only two ASCI counterparts at Sandia National Laboratories and Lawrence Livermore National Laboratory, respectively, as the millennium came to a close.

ASCI Q, the collaborative product of a partnership between Hewlett-Packard and Los Alamos, emerged as the world's second-fastest computer in 2002. Q eventually achieved a speed of 20 teraflops. But it would take the revolutionary hybrid cluster technology of Roadrunner to finally break the petaflop barrier in 2008, thus giving Los Alamos the world's fastest computer again for the first time since one of its Connection Machines, the CM-5, in 1993.

National Security and the Future of Scientific Innovation

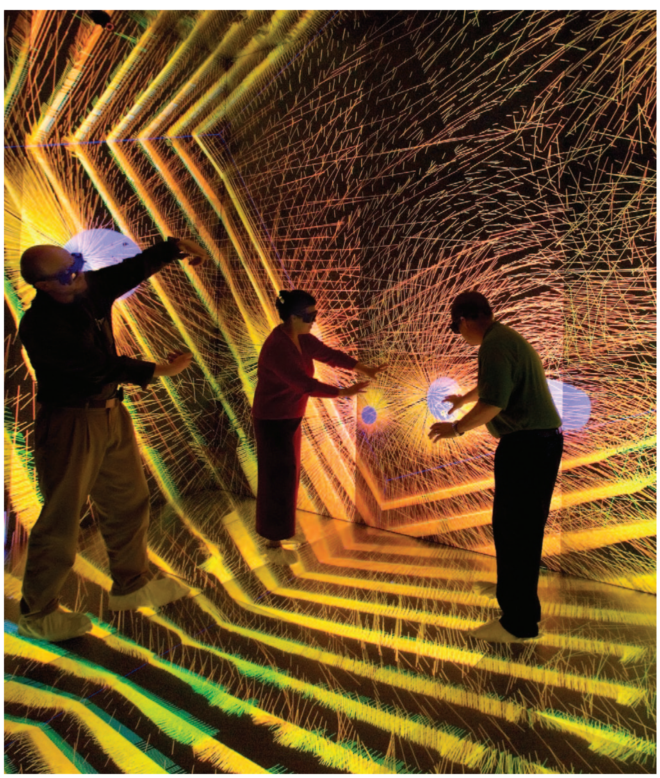
Throughout the Cold War, many of the world's most powerful computers were developed for national defense purposes, in particular for applications pertaining to the development and maintenance of nuclear weapons. During the Laboratory's 40th anniversary year of 1983, Frank Harlow and Nicholas Metropolis stated, "It is a stunning tribute to Los Alamos bomb designers and their colleagues that many of the most powerful procedures for taming computers to the myriad tasks of modern science and technology were developed right here."

Throughout the history of the Laboratory, computers have been specifically developed for the nuclear weapons program. Today, as the Laboratory turns 70, more-powerful computers enable more-detailed weapons simulations. More-detailed weapons simulations, supported by the Laboratory's experimental data, produce greater certainty in assessing the nuclear stockpile for safety and reliability. Greater certainty in assessing the nuclear stockpile ensures the nation will be able to maintain a credible nuclear deterrent well into the future.

But throughout the Laboratory's history, computers have also been used to further many fields of scientific endeavor. Biological explorations into the human genome, which continue today, can be traced all the way back to the 1950s, when Los Alamos scientists attempted to decode DNA sequences using MANIAC. Through the years, Laboratory computers have also been used for mineral exploration, basic science, and energy research. As we move deeper into the 21st century, Laboratory computers will continue to produce ever more detailed and accurate models for understanding global climate change, the spread of pandemics, and the nature of our universe, as well as the state of the nuclear weapons stockpile.

When Roadrunner broke the petaflop barrier, it inspired a new generation of supercomputers worldwide. These versatile machines enable scientists to perform research in a wide range of fields, but national security applications continue to play a significant role in driving the development of computing technology itself. In fact, as of November 2012**,** Department of Energy laboratories possess three of the four most powerful supercomputers in the world, including the fastest, Titan, a Cray machine at Oak Ridge National Laboratory. Roadrunner changed history, but it was not the first Los Alamos computer to do so. It will not be the last.

– *Alan B. Carr*



Today, Los Alamos' supercomputers enable scientists to run highly detailed 3D interactive simulations to solve problems in national security and general science. (Photo: Los Alamos)